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Detection of regime shifts in a shallow lake ecosystem based on multi-proxy paleolimnological indicators

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ABSTRACT

There have been significant regime shifts in the ecosystem structure and function in a large number of lakes worldwide due to the increasing human disturbance and climate change in recent decades. It has become a critical issue in lake conservation and management to identify the characteristics of regime shifts in lakes and explore potential early-warning signals prior to regime shifts. However, research on identifying and predicting regime shifts in lakes is still a difficult task since recent modelling approaches cannot fully grasp the non-linear processes among multiple ecosystem components and the ecological time series data are too scarce to support the detection in most lakes. In this study, multi-proxy paleolimnological records were used to obtain long time-series ecological data and determine the inflection points of regime shifts in the Baiyangdian Lake, northern China. First, the sediment chronology was established, and macrophyte pollen as well as nutrient conditions in each dated sediment layer were identified. Then the heuristic segmentation algorithm and Pettitt test were used to determine the most significant inflection points of regime shifts. Additionally, multiple early-warning indicators including variance, autocorrelation and skewness were used to test their ability to forecast the major ecosystem regime shift. Results show that the most important abrupt change in the Baiyangdian Lake occurred in the early 1960s. The increasing variance coupled with decreasing autocorrelation and skewness started in 1–16 years before this regime shift, which is consistent with a flickering phenomenon rather than critical slowing down. The detection results of regime shifts and early-warning signals can provide valuable reference information for the lake management and aquatic ecosystem conservation.

1. Introduction

Lakes as the key node of the hydrologic cycle and ecological processes in the watershed have played an important role in providing water resources, controlling floods, and maintaining the regional ecological balance. In recent decades, the water cycle and ecosystem status have altered significantly in a large number of lakes worldwide due to the increasing impacts of human disturbance and climate change (Arthington et al., 2010; Arnell and Gosling, 2013). Although the response of lake ecosystems to external disturbance is usually a gradual changing process, strong enough disturbances which overwhelmed the lakes' recovery ability could accelerate the ecological deterioration and lead to regime shifts of lake ecosystems (Cai et al., 2011; Poff and Zimmerman, 2010). Recent studies have shown that shallow lake ecosystems have generally exhibited alternative stable states (Scheffer et al., 2001). As for the shallow lake ecosystems, there are usually two mutually convertible stable states, i.e., the aquatic macrophyte-dominated clear water state and the phytoplankton-dominated turbid water state (Liu et al., 2013; Scheffer et al., 2001). An abrupt change from a clear water state to a turbid water state occurs when the perturbation (e.g., nutrient loads) passes a critical threshold, leading to sudden changes in the material and energy flows as well as the structure and function of lake ecosystems (Theissen et al., 2012). For example, eutrophication can lead to a severe loss of abundance and diversity of submerged macrophytes (Paillisson and Marion, 2011).

Exploring the characteristics and potential early-warning signals of the abrupt changes or regime shifts in lakes has become a critical issue in the lake conservation and management (Marín et al., 2014). However, it is still a difficult task to identify and predict the inflection points in lake ecosystems due to the incomplete understanding of inherent processes in the real lake ecosystems and the lack of long time series high-resolution data (Eason et al., 2014; Lindegren et al., 2012). On the one hand, it is difficult to fully grasp the complex relationship and non-linear processes among multiple ecosystem components, which often leads to inaccurate forecasting results (Cai et al., 2009; Zhao et al., 2013). On the other hand, various ecosystems differ greatly in the

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structures and functions, and the feature of regime shifts in special ecosystems may be fit for only a few unique ecosystems, which often leads to the poor universality of the existing early warning models (Yue et al., 2016). Additionally, the lack of long time series data with satisfactory resolution greatly hampers the detection in most lakes worldwide. Moreover, before fully understanding the mechanism of regime shifts in ecosystems and establishing reliable predictive models, some common indicators have been proved to be useful for monitoring whether the ecosystem state is close to a mutation threshold (deYoung et al., 2008; Qi et al., 2016). Previous studies show that many ecosystems before the critical transition exhibit similar characteristics or a series of general properties, which can be used as "early warning indicators" to predict whether the ecosystems have a trend of critical transition (Scheffer et al., 2009). For example, the variance of system status variables will increase when the system fluctuates more dramatically near the equilibrium status (Carpenter and Brock, 2006). The slower recovery rate before critical transition may also be signaled by the increasing trend of autocorrelation and skewness (Wang et al., 2012).

Paleolimnological technology has been widely applied to obtain long time-series ecological data for coping with the problems of data deficiencies, which can also provide evidence of influence of climate change and human disturbance on regime shifts of lake ecosystems (Sayer et al., 2012). Paleolimnological techniques, which use various ecological indicators such as pollen, diatoms, chironomids and ostracods, have been widely used to reconstruct historical ecological conditions, detect trends of climate change and evaluate the lake eutrophication (Costa-Böddeker et al., 2012; Garreta et al., 2012; Wischnewski et al., 2011). Among these ecological indicators, macrophyte pollen can effectively represent the growth states of aquatic plants and reflect historical environmental conditions of lakes (Davidson et al., 2010; Salgado et al., 2010). This paper presents a case study on the nature of regime shifts in the Baiyangdian Lake with multi-proxy paleolimnological data. First, the sediment chronology was established, and macrophyte pollen as well as nutrient concentration in each dated sediment layer were identified. Then the heuristic segmentation algorithm and Pettitt test were used to determine the most significnat inflection points of regime shifts. Additionally, multiple early-warning indicators including variance, autocorrelation and skewness were used to test their ability to forecast the major mutation in the lake ecosystem. The detection results of regime shifts and early-warning signals can provide valuable reference information for the lake management and aquatic ecosystem conservation.

2. Materials and methods

2.1. Site description

The Baiyangdian Lake (between 38°43′ − 39°02′N, 115°38′ − 116°07′E) is the largest plant-dominated freshwater lake in the North China Plain, with the largest surface area of about 366 km^2 (Fig. 1). Historically, eight rivers including the Zhulong, Xiaoyi, Tang, Fu, Cao, Pu, Ping, and Baigou River flowed into the Baiyangdian Lake, and the average annual water level ranged from 5.2 m to 11 m during 1919 and 2012 (the average elevation of the lake bottom is 5.2 m). This lake has irreplaceable ecological and social functions such as regulating water cycle, supporting high biological productivity and biodiversity and maintaining ecological balance of its surroundings regions (Yang and Yang, 2013). A large number of submerged and emerged plants are dominant in this lake, and the main species include *Poaceae*, *Typhaceae*, *Polygonaceae*, *Nymphaeceae*, *Ranunculaceae*, *Gentianaceae*, *Cruciferae*, *Potamogetonaceae*, *Cyperaceae*, and *Haloragaceae*.

The annual average water inflow of the Baiyangdian Lake has generally decreased since the late 1950s due to climate change as well as the flow regulation of three large dams (Xidayang Reservoir, Wangkuai Reservoir and Angezhuang Reservoir) in its upper reaches. For example, the inflow of the Baiyangdian Lake in the 1950s, 1960s, 1970s, 1980s, 1990s and 2000s was 1.94, 1.90, 1.03, 0.20, 0.43 and 0.10 billion m^3, respectively. Low or no inflows caused the decreasing water level and increasing concentration of pollutants (Yang et al., 2014). It is an urgent issue in supporting lake management to explore how variation of hydrological conditions and water quality degradation influenced the variation of ecological states of the Baiyangdian Lake.

2.2. Sediment sampling and radiometric dating

Recently, some parts in the Baiyangdian Lake have suffered from considerable human disturbance such as dredging and planting. In order to guarantee the collected sediment core can accurately record historical conditions, a stable region with less human activities was selected as the sampling site. In this study, four sites were firstly identified as candidates with Google Earth and field investigation; then, lithological characteristics (color and grain) in the trial core (40 cm length) collected in each site were compared, the corresponding site of which shows the consistent trend and clear grain is fit for this study. Finally, a 95 cm deep sediment core was collected with a gravity corer in the Shaochedian sampling site in June 2012. The core was cut into 1 cm intervals in the field and saved in plastic bags at 4 °C before returning to the laboratory. In the laboratory, each section was freeze dried into constant weight of about 15–30 g for further treatment.

Dating of the sediment core from the Shaochedian sampling site used ^{210}Pb and ^{137}Cs dating techniques. The ^{210}Pb is a natural radionuclide, which can be used to date sediments from the last 100–150 years. ^{137}Cs is an artificial radionuclide, and ^{137}Cs in the sediment profile was caused by nuclide scattering events including nuclear weapon testing in 1963 and 1974–1975 (Álvarez-Iglesias et al., 2007), the Chernobyl accident in 1986, and the Fukushima Daiichi nuclear disaster in 2011. Therefore, ^{137}Cs can be applied for dating for the last 50 years (Seddon et al., 2012). In this study, all of the sediment intervals were analyzed for ^{210}Pb and ^{137}Cs with direct gamma spectrometry at the Nanjing Institute of Geography & Limnology, Chinese Academy of Sciences. The ^{210}Pb chronology was calculated based on the constant rate supply model (CRS model; Appleby and Oldfield, 1978). Profiles of ^{137}Cs activities in the sediment core were applied to validate the ^{210}Pb chronology. The result of ^{210}Pb dating was further verified with peak ^{137}Cs values across the whole sediment core (Bigelow and Edwards, 2001).

2.3. Analysis of macrophyte pollen and environmental factors

The Baiyangdian Lake is a typical plant-dominated lake, and biomass of macrophytes accounted for the largest portion of the whole lake ecosystem (Yang et al., 2014). Changes of abundance and composition of macrophytes are essential for the material cycle and energy flow among species in upper trophic levels; meanwhile, since macrophytes have a good absorbing ability of nutrients in the water body, it can also influence the water quality of the lake (Zhao et al., 2012). Macrophyte pollen was selected as the ecological indicator in this study because it can reflect the abundance and composition of macrophytes during the historical period in a lake (Davidson et al., 2005). In this study, 5 g subsamples from each 47 samples (taken at 2 cm intervals from 1 to 95 cm) were treated to extract pollen according to the standard procedure (Faegri and Iversen, 1989) in the Pollen Analysis Laboratory at Hebei Normal University. First, the samples were sieved through 200 μm mesh screens to remove small animals and plant fragments, and one tablet containing 27637 ± 563 *Lycopodium* spores was added as a tracer to each sample for estimating pollen concentration and accumulation rates. Then, samples were treated with 10% HCl, 10% NaOH, and 40% HF reagent, washed with distilled water, and sieved through 10 μm mesh screens. Thereafter, the samples were floated with gravity liquid, and the suspensions were centrifuged and acetolysed before being mounted on slides for counting. A BX-51 Olympus light

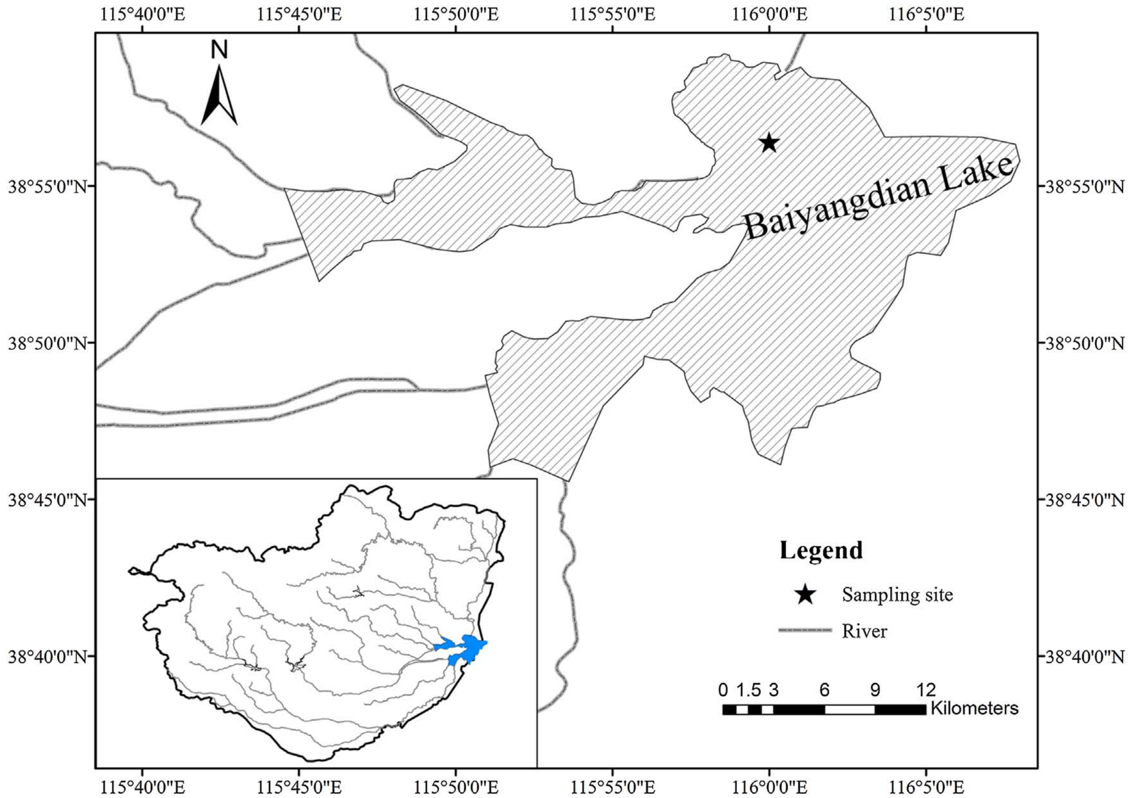

Fig 1. Map of the study area and location of the sampling site.

microscope at ×400 magnification was used to identify and count pollen in each sample (Xu et al., 2012).

Abundance of a certain type of pollen was expressed as the percentage of grains of this type to the number of total grains. Concentration of a certain type of pollen was determined according to the two ratios: the ratio of *Lycopodium* number added to the sample and *Lycopodium* number counted in the sample; and the ratio of a certain type of pollen grains and the sample weight. The stratigraphic distributions of pollen abundance and concentration were plotted using the TILIAGRAPH software (Grimm, 1991). The boundaries of assemblage zones were delineated according to a constrained cluster procedure (CONISS) implemented with the TILIAGRAPH software.

In order to explain the alteration trends of the abundance and composition of macrophyte during the historical period, some environmental factors which reflect the geochemical, hydrological and climatic conditions in this lake were further analyzed. The analyzed geochemical parameters include total nitrogen (TN), total phosphorus (TP), total organic carbon (TOC), chroma and magnetic susceptibility. TP and TN concentrations in each layer were determined with the molybdenum blue spectrophotometric method and Kjeldahl nitrogen determination method, respectively. The TOC concentration was analyzed on a Shimadzu TOC-V analyzer. Magnetic susceptibilities were measured with a Bartington MS2 magnetic susceptibility meter (Adams et al., 2014; Álvarez-Iglesias et al., 2007). Monthly water level records for the Baiyangdian Lake from 1919 to 2011 were obtained from the Water Conservancy Office in Baoding City, Hebei Province. Monthly precipitation and temperature data from 1906 to 2012 at the Baoding meteorological station were acquired from the China Meteorological Data Sharing Service System.

2.4. Trend and abrupt change analysis

In this study, trend and abrupt change analysis of abundance of macrophytes was implemented to identify the regime shift in a grassy shallow lake. Both the heuristic segmentation algorithm and Pettitt test were applied in order to cross-validate the detection results. Although various statistical methods such as the sliding T test, Mann-Kendall test, Yamamoto test have been commonly used to detect inflection points in the time series, most of them are based on the assumption that the data are linear and smooth (Huang et al., 2016). Since ecological time series are highly nonlinear and have great variability, the heuristic segmentation algorithm proposed by Bernaola-Galván et al. (2001) was introduced in this study. This algorithm modified based on the sliding T test and have an advantage in detecting the inflection point of nonlinear and non-stationary time series, and its main principle is as follows:

A sliding pointer is moved from the left end to the right end of the time series (Bernaola-Galván et al., 2001), and the averages of the subsets of the series to the left of the pointer (μ_{left}) and to the right of the pointer (μ_{right}) are calculated at each position of the pointer. The difference between μ_{left} and μ_{right} at a given statistical significant level is estimated by Student's t-test statistic as follows:

$$t = \left| \frac{\mu_{left} - \mu_{right}}{S_d} \right| \tag{1}$$

$$S_d = \left(\frac{(N_{left} - 1)s_{left}^2 + (N_{right} - 1)s_{right}^2}{N_{left} + N_{right} - 2} \right)^{1/2} \left(\frac{1}{N_{left}} + \frac{1}{N_{right}} \right)^{1/2} \tag{2}$$

where s_{left} and s_{right} are the standard deviation of the two subsets, N_{left} and N_{right} represent the number of the two subsets.

A larger t means that the average values of the two time series tend to be more significantly different. The largest t value is regarded as a good candidate for the cut point. Then, the position of the pointer for which t reaches its maximum value, t_{max}, was determined, and its significance was checked by comparing $P(t_{\max})$ with a threshold, P_0 (typically 0.95), where:

$$P(t_{max}) \approx \left\{1 - I_{[(N-2)/N-2+t_{max}^2]}(\delta(N-2), \delta)\right\}^{\eta} \tag{3}$$

where $\eta = 4.19\ \ln N$-11.54 and $\delta = 0.40$ are acquired from Monte Carlo simulations, N is the length of the time series to be segmented. If the

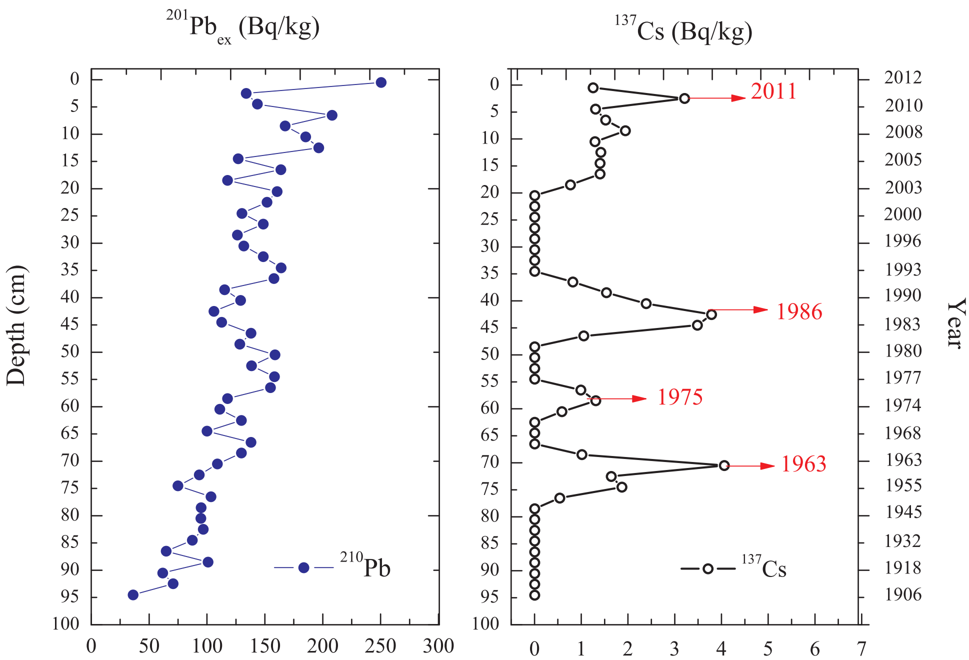

Fig. 2. (a) ^{210}Pb (b) and ^{137}Cs activity-depth profiles in the Baiyangdian Lake core.

difference between the mean values is not statistically significant ($P(t_{max})$ is less than P_0), the time series will be not divided. Conversely, the time series is divided into two segments with significantly different averages. If the time series is divided, the iteration of the above procedure on each new segment will continue until no further change point can be found or the length of the acquired segments are less than the presupposed minimum segment length l_0, determined as 25 according to Huang et al. (2016).

The Pettitt test was selected due to it has an advantage in trend detection and could be used to identify the most significant change point (Jiang et al., 2011; Huo et al., 2013). The Pettitt test considers a series with N samples as two sub-samples represented by $x_1,\ldots,x_t$ and $x_{t+1},\ldots, x_N$, and a version of the Mann-Whitney statistic $U_{t,N}$ can be calculated by the following formulas (details please see Pettitt, 1979):

$$U_{t,N} = U_{t-1,N} + \sum_{j}^{N} sgn(X_t - X_j), (t = 2, \cdots\cdots, N) \tag{4}$$

where

$$\mathrm{sgn}(x) = \begin{cases} 1, if x > 0 \\ 0, if x = 0 \\ -1, if x < 0 \end{cases} \tag{5}$$

The test counts the number of times a member of the first sample exceeds a member of the second sample. Pettitt's statistic can be given as:

$$K_t = Max|U_{t,N}|1 \leq t \leq n \tag{6}$$

The most significant change point occurs where the value of $U_{t,N}$ is maximum. The significant level is determined approximately by Eq. (7). The null hypothesis of the Pettitt test is that there is no change point. If P is less than a certain significant level, e.g. 0.01 in this study, the null hypothesis is rejected, and a significant change point can be identified in this time series (Jiang et al., 2011).

$$P = 2\exp\{-6(K_t)^2/(N^3 + N^2)\} \tag{7}$$

2.5. Early-warning signal detection

Recent studies show that systems before approaching regime shift usually exhibit similar characteristics, and therefore a series of generic properties can be used to describe the similar characteristics and regarded as common early-warning signals in different systems (Scheffer et al., 2009). Variance, autocorrelation and skewness have been widely used as early-warning indicators for describing two major phenomena prior to a regime shift on the temporal dimension (Guttal and Jayaprakash, 2008). One phenomenon is critical slowing down. When an ecosystem is close to regime shift threshold, the recovery from small perturbations becomes slower, leading to critical slowing down (Carpenter and Brock, 2006). Rising levels of variance, autocorrelation, and skewness are considered as single of critical slowing down. Flickering is reflected by increasing variance, coupled with decreases in autocorrelation and skewness (Wang et al., 2012).

The lag-1 autocorrelation coefficient of state variables were calculated as:

$$\rho = E[(Z_t - \mu)(Z_{t+1} - \mu)]/S_z^2 \tag{8}$$

Variance was represented by standard deviation (SD) of the time series of state variables:

$$S^2 = \sum_{i=1}^{n} (Z_t - \mu)^2/n \tag{9}$$

The absolute value of skewness (S_k) for time series data was calculated as follows:

$$S_k = \frac{1}{n}\sum_{i=1}^{n} (Z_t - \mu)^3/\sqrt{\frac{1}{n}\sum_{i=1}^{n} (Z_t - \mu)^2} \tag{10}$$

where μ and S_z^2 denote the average and variance of state variable Z_t, respectively.

Furthermore, the relationships between pollen and environmental factors are assessed to validate the inflection points of regime shift and early warning signals in the lake ecosystem.

3. Results and discussions

3.1. ^{137}Cs and ^{210}Pb chronology

Fig. 2 shows the dating results based on vertical profiles of ^{210}Pb and ^{137}Cs activities in the 95 cm sediment core from the Bayangdian Lake. ^{137}Cs activities had four well-defined peaks between 1 and 77 cm depths, probably recording the fallout from the Fukushima Daiichi

nuclear disaster in 2011, Chernobyl accident in 1986, and nuclear weapons testing in 1974–1975 and 1963 (Álvarez-Iglesias et al., 2007; Seddon et al., 2012). Raw $^{210}Pb_{ex}$ dates place 2011, 1986, 1974, and 1963 at the depths of 2 cm, 44 cm, 61 cm, and 70 cm, respectively, which are in relatively good agreement with the depths determined from the ^{137}Cs records (Fig. 2a). Corrected dates were calculated by applying the CRS model in a piecewise way using the ^{137}Cs dates for reference (Appleby, 2001). Finally, the dates of the 95 cm long core were determined to be between 1906 and 2012. The sediment deposition rate ranged from 0.24 to 2.56 cm y^{-1}, with an average value of 1.08 cm y^{-1}.

3.2. Temporal trend of pollen and environmental factors

The Baiyangdian Lake is a grassy shallow lake that supports high macrophyte productivity, and the lacustrine sediment is characterized by wide varieties and high concentrations of macrophyte pollen. According to the historical investigations in this lake, the primary aquatic plants include *Poaceae*, *Typhaceae*, *Polygonaceae*, *Nymphaeceae*, *Ranunculaceae*, *Gentianaceae*, *Cruciferae*, *Potamogetonaceae*, *Cyperaceae*, *Haloragaceae*. Fifty-five pollen taxa were identified in the sediment profile, 11 of which were from aquatic macrophytes. Concentration of macrophyte pollen accounted for approximately 58.7% of the total pollen (ranging from 44.0% to 72.8%) (Fig. 3). According to the plant life-form, the major taxa of macrophyte pollen can be categorized into four groups: hygrophilous plant (*Cyperaceae*, *Cruciferaceae*), emerged plant (*Poaceae*, *Typha*, *Polygonaceae*), submerged plant (*Potamogetonaceae*, *Myriophyllum*, *Ranunculaceae*), and green algae (*Pediastraceae*). Two major assemblage zones and 10 sub-zones can be identified based on the CONISS analysis (Fig. 3). The year of 1963 in correspondence to the depth of 70 cm is the most important separate year of pollen assemblages during 1906 and 2012. In Zone I (depth 70–94 cm), the average percentage of *Cyperaceae* was lower than that in the other zones. Zone I can be further divided into three sub-zones according to the main pollen types: I-a (88–94 cm), I-b (82–86 cm), and I-c (70–80 cm). From I-a to I-b, the contents of *Myriophyllum* and *Potamogetonaoeae* increased, indicating that water level increased during this period. Then the percentage of *Poaceae* (mainly common reed) and *Cyperaceae* increased, indicating the climate turned humid. In addition, the pollen concentration changed significantly in sub-zone I-b, with the average total pollen concentration reaching 30,000 grains/g, which is the highest in the entire profile. Compared with Zone I, pollen assemblages in Zone II (depth 2–68 cm) changed more dramatically. The content of *Cyperaceae* increased significantly, whereas the contents of *Cruciferae*, *Potamogetonaceae*, and *Myriophyllum* decreased considerably. *Cyperaceae* and *Pediastraceae* in sub-zone II-a (62–68 cm) increased more significantly than that in sub-zone I-c, indicating the water level became lower during this period. Pollen concentration in sub-zone II-b (52–60 cm) is much lower than that in sub-zone II-c (42–50 cm). In sub-zone II-c, the content of *Poaceae* decreased, whereas the total concentration of aquatic pollen increased to the second highest value in the whole profile. By comparison, in sub-zone II-d (34–40 cm), pollen concentration decreased, and aquatic pollen concentrations stayed at a low level from sub-zone II-e (24–32 cm) to sub-zone II-g (2–12 cm). In sub-zone II-g (2–12 cm), the contents of *Cyperaceae* and *Myriophyllum* decreased gradually. This result shows that *Poaceae*, *Cyperaceae*, and *Chenopodiaceae* are dominant in all samples, and the compositions and concentrations of macrophyte pollen assemblages

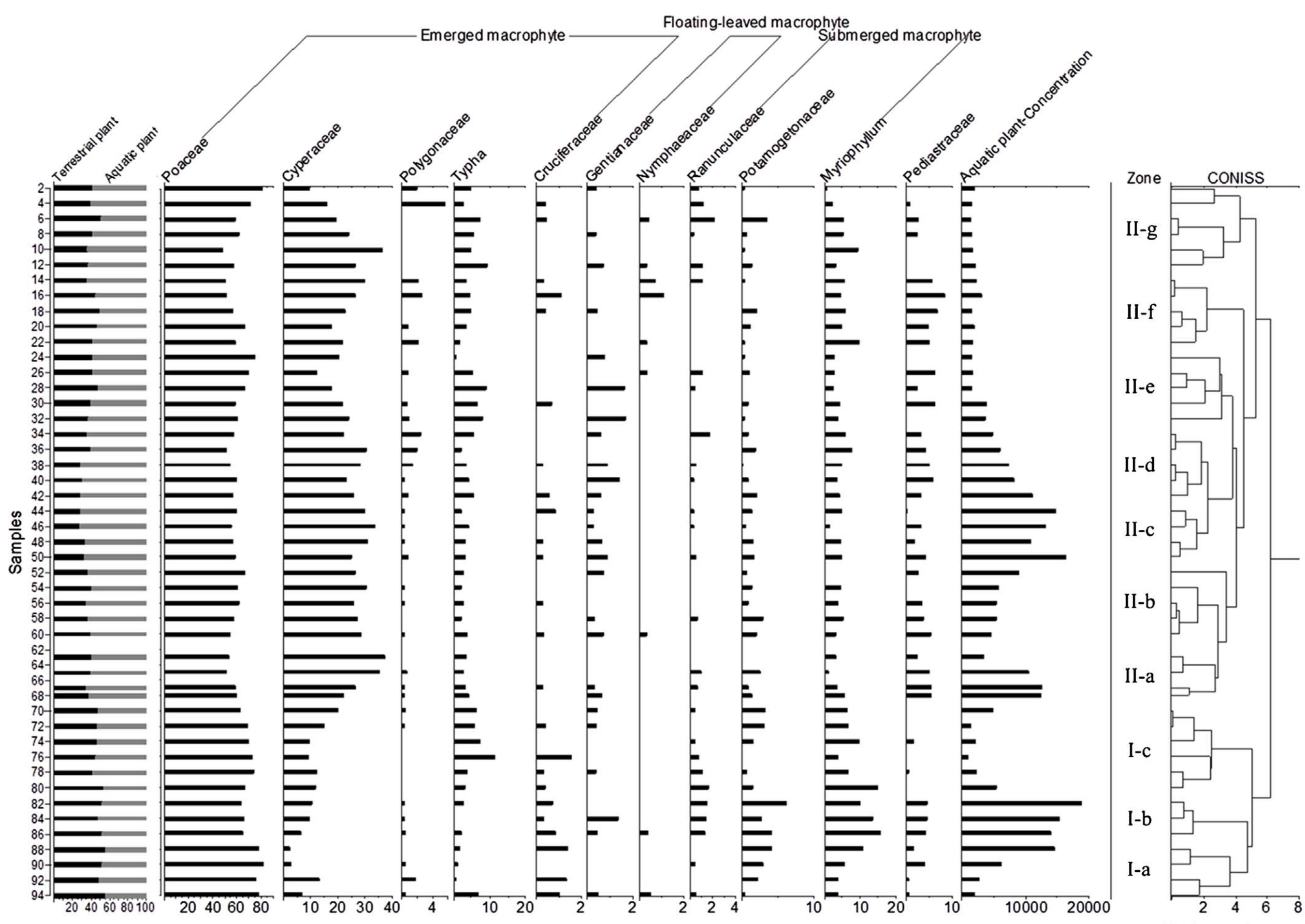

Fig. 3. Summary of the pollen assemblages from the core in the Baiyangdian Lake and macrophytes pollen based zonation.

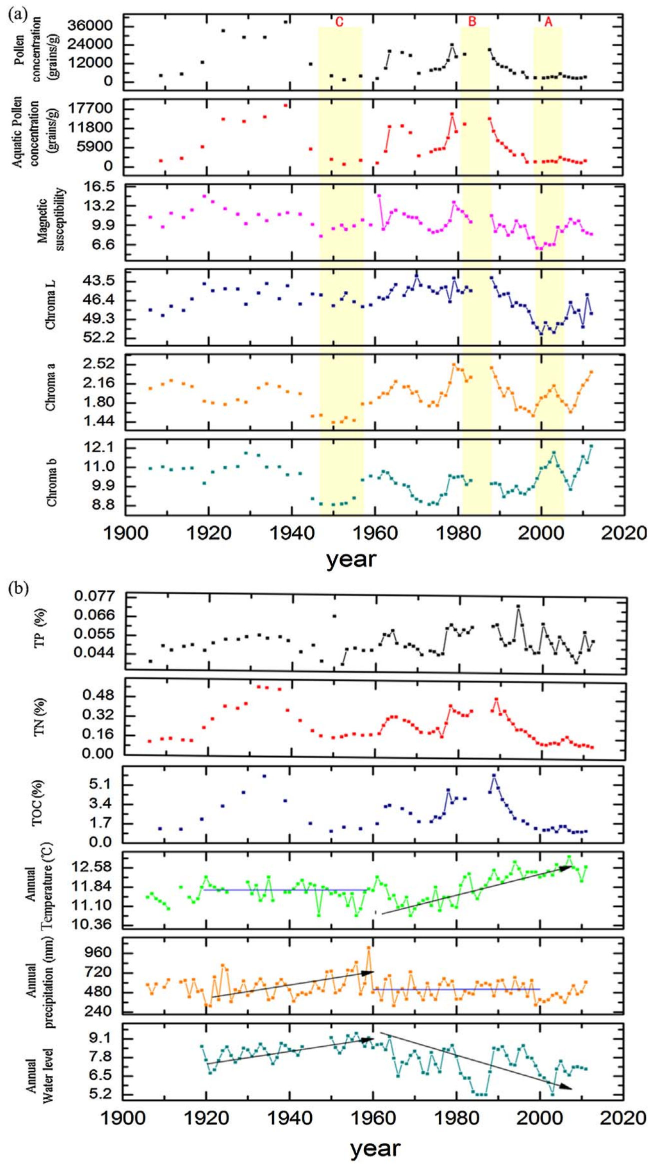

Fig. 4. The diagram of ecological and environmental sequences during 1906 and 2012 in the Baiyangidan Lake: (a) pollen concentration, magnetic susceptibility, and chroma (a, b, L); (b) concentrations of TP, TN, and TOC, monitoring record of annual precipitation, temperature and water level.

have changed significantly during the study period.

The significant positive correlation between aquatic pollen concentration and TOC (0.677 $P < 0.01$) suggests that aquatic plant is a major source of total production in the lake ecosystem (Fig. 4). Geochemical condition and macrophyte pollen concentration in the sediment profile shows three noteworthy trends: (1) from 2000 to 2005, the peak values of chroma a and chroma b indicate the oxidation state of the lake is enhanced (Fig. 4a). During the same period, the values of chroma L, TOC, total pollen concentration, aquatic pollen concentration, and nitrogen content were low, indicating the lake was in a relatively dry state during this period. (2) From 1976–1985, the values of total pollen concentration, aquatic pollen concentration, TOC, chroma a, chroma b, and chroma L are all at higher peak states. The water level maintained a moderate level during this period. Aquatic plants flourished during this period, suggesting that moderate water level in the Baiyangdian Lake is suitable for the growth of aquatic plants. (3) From 1947–1957, the values of the total pollen concentration, aquatic pollen concentration, TOC, chroma a and chroma b were in a low state. However, water level during this period is higher than that during other periods, reflecting the expansion of the lake and the increase of water depth. The growth of aquatic plants near the sampling site was inhibited due to the high water level.

3.3. Regime shift of the baiyangdian lake

The abandance of four macrophyte groups were selected as ecological indicators to represent the dynamic alterations of ecosystem during the chronology period. Data corresponding to sediment layers were interpolated into annual data series with the linear interpolation method in order to facilitate the further calculation process.

Fig. 5 shows the detection results by the heuristic segmentation algorithm on the annual abundance of emerged plant, hygrophilous plant, submerged plant, and *Pediastraceae*. As for the abundance of emerged plant, five inflection points (1926, 1947, 1963, 1975 and 1993) were identified as possible abrupt change locations due to the corresponding values of $P(T_{max})$ are all equal to 1 and are greater than P_0 ($T_{\max}$ is 24.66, 29.57, 27,14, 8.21 and 10.00, respectively). For the abundance of hygrophilous plant, abrupt changes appeared in the year of 1934, 1963, 1966 and 1989, with the conditions that $P(T_{\max}) = 1$, 1, 0.99, 1 $>$ P_0 (corresponding $T_{\max}$ is 23.00, 41.93, 5.00 and 21.11, respectively). For the abundance of submerged plant, the year of 1922, 1945, 1964 and 1986 were identified as inflection points due to the values of $P(T_{\max})$ are equal to 1, 0.99, 1, 1, respectively, which are greater than P_0 (corresponding $T_{\max}$ is 40.79, 5.95, 26,51, and 8.04, respectively). For the abundance of *Pediastraceae*, the year of 1917, 1942, 1964 and 1989 were identified as possible abrupt change locations since the values of $P(T_{\max})$ are equal to 1, 1, 1, 0.99 and are greater than P_0 (corresponding $T_{\max}$ is 20.65, 31.23, 24.74 and 5.97, respectively). Results show that each detected series can be divided into several segments by the 4 or 5 inflection points, which further proved that macrophyte abundance during 1906–2012 showed some nonlinear and non-stationary features. Multi-inflection points in different time series have similar locations, particularly, the abrupt change in approximately 1963–1964 has been identified in each time series.

Table 1 shows the detection results by the Pettitt test. The most significant inflection points for annual abundance of emerged plant, hygrophilous plant, submerged plant, and *Pediastraceae* occurred in 1963, 1960, 1963 and 1963 respectively. Inflection points detected by the heuristic segmentation algorithm reflect significant differences among the averages of the subsets of the analyzed series, while those detected by the Pettitt test reveal the most significant change in trends for the series (Liang et al., 2010). Combining the detection results from both methods, the inflection points for abundance of emerged plant, hygrophilous plant, submerged plant, and *Pediastraceae* were finally determined as 1963, 1960–1963, 1963–1964 and 1963–1964, respectively. This detection result is consistent with the major boundaries of pollen assemblage zones delineated with CONISS in TILIAGRAPH, which further confirmed the robustness of the most important regime shift that occurred in the early 1960s. The averages, variances and coefficient of variation (CV) values of the abundance of the four macrophyte types before and after the 1960s were also summarized in Table 1. The average emerged plant, submerged plant showed a downward trend, meanwhile the average hygrophilous plant and green algae increased during the post-inflection period. The variances of the four macrophyte categories before and after the inflection points are also notably different.

In addition, characteristics of hydrological and meteorological sequences show significant differences before and after the 1960s (Fig. 4b). From the 1920s to the 1960s, regional precipitation increased slowly, temperature fluctuation were not significant, meanwhile water level in the Baiyangdian Lake increased slowly. Since the 1960s, the air temperature increased significantly, meanwhile precipitation fluctuated were at low conditions, and the lake level declined significantly.

The inflection points in 1960–1964 are also close to the time of the construction of reservoirs in the Baiyangdian Catchment (Moiwo et al.,

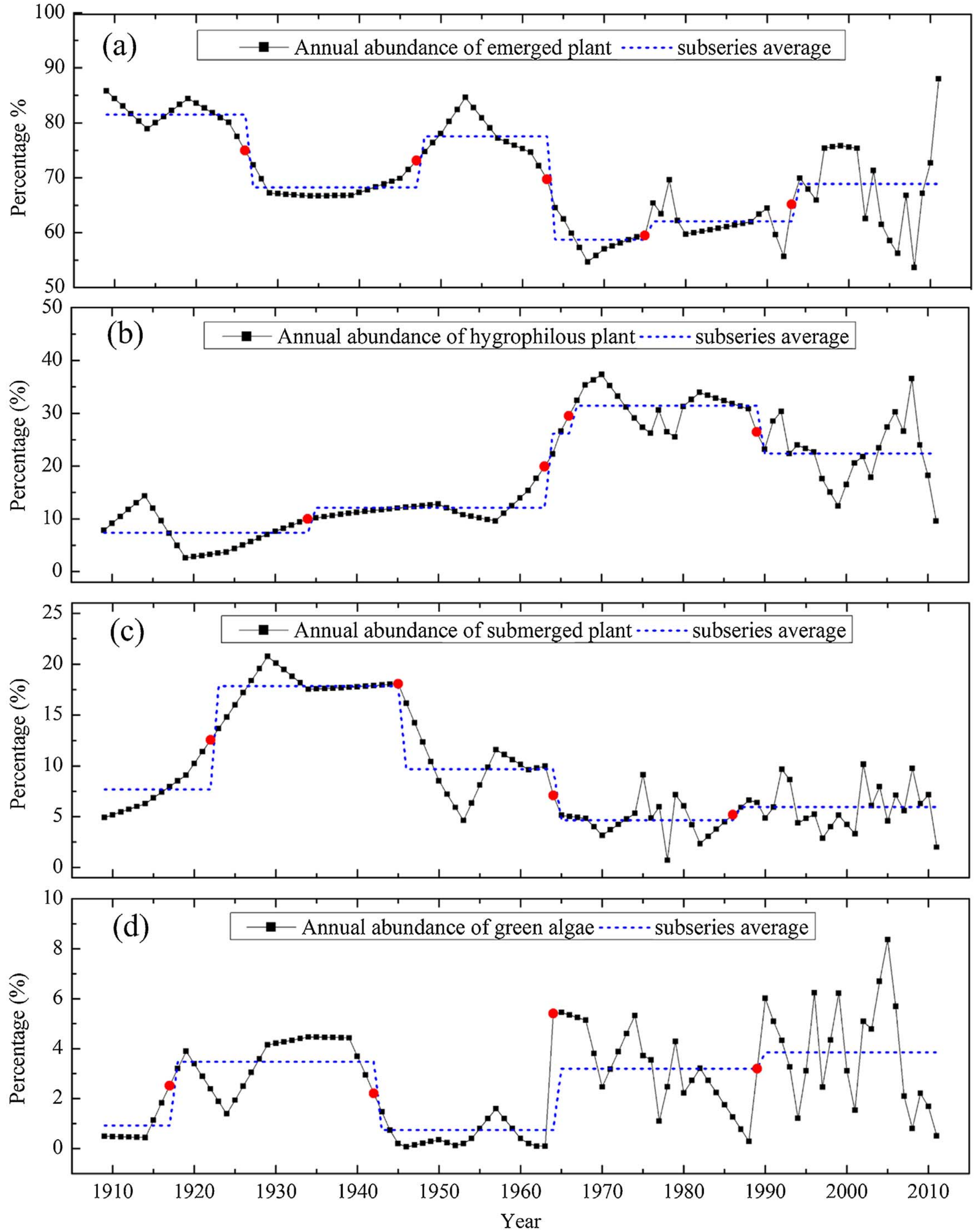

Fig. 5. Inflection points and segmentations of annual abundance of emerged plant (a), hygrophilous plant (b), submerged plant (c) and green algae (d). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

Table 1
Pettitt test results of macrophytes' abundance during 1906 and 2012 and statistical values before and after the most significant inflection points.

Categories	Pettitt test	Significant level	Combined two method	Time series	Average	Variance	Variation coefficient
emerged plant	1963	$P < 0.001$	1963	1909–1963	75.29	41.57	0.09
				1964–2011	63.77	48.63	0.11
hygrophilous plant	1960	$P < 0.001$	1960–1963	1909–1960	9.41	10.29	0.34
				1963–2011	26.81	43.24	0.25
submerged plant	1963	$P < 0.001$	1963–1964	1909–1963	12.62	25.43	0.40
				1964–2011	5.37	4.05	0.37
green algae	1963	$P < 0.01$	1963–1964	1906–1963	1.93	2.66	0.84
				1964–2011	3.55	3.44	0.52

2010). In order to meet the needs of agriculture, rapid development of industry and the explosion of urban population, six large scale reservoirs and more than 90 small scale reservoirs with a total storage capacity of 3.6 billion m^3 were constructed in the upstream rivers of the catchment in the late 1950s and the early 1960s. Alteration of flow regimes caused by reservoir regulation can interrupt hydraulic interconnections among aquatic ecosystems such as rivers, lakes and marshes (Lake, 2003; Guo et al., 2012), reduce the area of the acceptable habitat for most aquatic biota, and cause invasion of non-native species (Suen and Eheart, 2006).

3.4. Indicators for early-warning purpose

We further explored whether there are early-warning signals before the regime shifts occurred. In this study, more than one inflection points have been detected in each nonlinear time series during the last 100 years. In order to assess the significance of alteration trend of variation, skewness and autocorrelation, only the most significant inflection year was considered in each ecological time series. For annual abundance of emerged plant, hygrophilous plant, submerged plant, and *Pediastraceae*, the most significant inflection year is 1963, 1960–1963, 1963–1964 and 1963–1964, respectively, and 40 years were selected as the slide window for calculation. As the results in Fig. 6 shows, the slide window of 40 years can effectively represent the trend of variation, skewness, and autocorrelation for different ecological time series during 1906 and 2012. For emerged plant and hygrophilous plant, the trend of variance increased at 1962, 1957, respectively (Fig. 6a). The variance series of emerged plant and hygrophilous plant increased near the abrupt change year 1963 and 1960, respectively. For submerged plant, the temporal variance increased in about 5 years prior to the abrupt change year 1963. In the case of green algae, the variance increased in about 16 year before the most significant abrupt change took place (Fig. 6b). The rising variances indicate fluctuation increased before the critical transition. On the contrary, autocorrelation of the four types of macrophytes demonstrated continuous declining trends during the detected period. Local declining trends started in 2, 4, 2 and 6 years before regime shifts of emerged plant, hygrophilous plant, submerged plant, and green algae, respectively (Fig. 6c-Fig. 6d). Meanwhile, skewness of emerged plant, hygrophilous plant, submerged plant and algae demonstrated a declining trend near the inflection point during 1962–1969, 1957–1963, 1959–1972 and 1954–1962, respectively (Fig. 6e–f).

Results in this study show that the critical transition occurred in 1960–1963 of the Baiyangdian Lake, which was partly presaged by signals of rising variance, declining skewness and autocorrelation in about 1–16 years before. Since critical slowing down was characterized by increased variance, skewness and autocorrelation, the declines of skewness and autocorrelation of macrophytes' abundance in the Baiyangdian Lake cannot be fully explained by this phenomenon. They are most likely to represent flickering, which is another phenomenon in the vicinity of a mutation. Flickering usually occurs if the sudden and huge disturbance happens, and the disturbance is strong enough to move the system back and forth between the basins of attraction (Scheffer et al., 2009). Since this regime shift is not derived from the gradual shrinkage of cumulative elasticity, there is no critical slowing down phenomenon but the frequent fluctuation in the vicinity of the

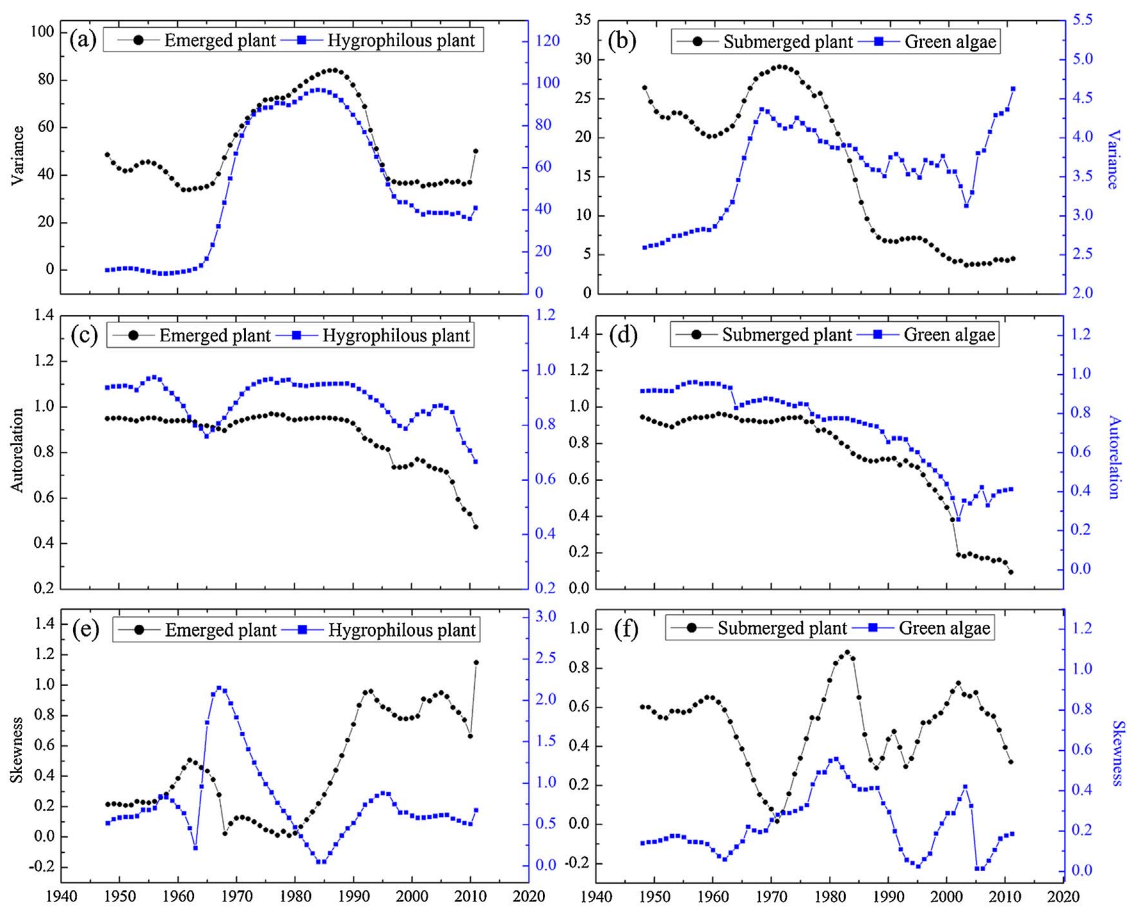

Fig. 6. The trend of potential early warning signals: (a) variance temporal series for hygrophilous plant and emerged plant; (b) variance temporal series for submerged plant and green algae; (c) autocorrelation temporal series for hygrophilous plant and emerged plant; (d) autocorrelation temporal series for submerged plant and green algae; (e) skewness temporal series for hygrophilous plant and emerged plant; (f) skewness temporal series for submerged plant and green algae. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

regime shift. Flickering also can be attributed to the noise generated solely by internal changes of the system. However, multiple environmental drivers can be considered as major reasons for flickering in the Baiyangdian Lake, due to the strong evidence for the alteration of macrophytes and environmental factors in the beginning of the 1960s (Fig. 4).

Although identifying regime shifts and early-warning signals is useful in informing timely management actions in the face of ecosystem changes, there are still some limitations in this study. For example, this study only discussed critical slowing down or flickering phenomenon on the temporal dimension. It is still necessary to obtain special data for further special dimension analysis. Because early-warning detection usually depends on the choice of metrics and the use of sliding windows, differences among scenarios should be discussed in further study.

4. Conclusions

Critical transitions between alternative stable states have been proved to occur across an array of complex ecosystems. This study used paleolimnological records of key ecosystem components to analyze the succession processes and detected the inflection points of ecological status and early-warning indicators before abrupt changes in a shallow plant-dominated lake in China. The following conclusions can be drawn:

(1) The paleolimnological approach is effective for obtaining long-term ecological data and analyzing the variation trends of the lake ecosystem. Pollen profiles from a sediment core in the Baiyangdian Lake supports the assumption that the sediment parameters can indirectly reflect the environmental characteristics and composition of macrophytes. The average abundance of emerged plant, submerged plant showed a downward trend, meanwhile the average abundance of hygrophilous plant and green algae showed an increased trend after the early 1960s.

(2) The most significant regime shift in the Baiyangdian Lake occurred in the early 1960s mainly due to the mixed impacts of dam regulation and climate change. Rising variance coupled with decreasing autocorrelation and skewness started in 1–16 years before the regime shift. This finding tends to be more consistent with a flickering phenomenon rather than critical slowing down. The flickering phenomenon is more likely to occur than critical slowing down is when the shallow lake ecosystem suffered from sudden exogenous disturbance.

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